Progress Report, Year-1 (2000-2001)

Experimental and Theoretical Analysis of Flashing Instability for Next Generation Natural Circulation Reactors

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The project titled above has progressed according to the schedule outlined in the original proposal. In fact, some of the tasks scheduled for the second year of the project have already been started. It is hoped that the tasks scheduled for year 2 will be completed in time, and we may even be able to start a few of the tasks for year three before the end of the second year.

A simulator with significantly enhanced modeling and simulation capabilities has been developed to analyze flashing and flashing-induced-instabilities. Specifically, the following tasks have been completed.

Starting from single and two-phase flow equations for the heated core and the riser section, a model has been developed that allows an arbitrary number of nodes in both the heated section (allowing axially varying heat flux) and in the un-heated riser section. The saturation enthalpy in this model is a function of pressure. Pressure dependent enthalpy leads to a modified energy equation, and introduces a new dimensionless quantity, *flashing number*, which is equal to zero when the saturation enthalpy is taken to be a constant. The data for water shows that a quadratic polynomial can very well capture the dependence over a wide range of pressures of interest. Both, linear and quadratic dependence of saturation enthalpy on pressure are being used.

A Galerkin-type approach is employed to reduce the partial differential equations—that arise during the modeling stage—to a dynamical system form (a set of nonlinear ODEs). In this approach, after dividing the entire physical domain into physically meaningful subdomains, trial functions with time-dependent coefficients are introduced to describe the *spatial* dependence of the dependent variables in each subdomain. These *trial functions* are substituted in the relevant PDEs, which are then integrated over the respective subdomains, leading to a set of ODEs for the (time-dependent) coefficients.

The model equations and the reduced form are too lengthy to be included in this progress report. The final set of nonlinear ODEs are written symbolically as $\frac{d\,\underline{X}(t)}{dt} = \underline{F}(\,\underline{X}\,;\boldsymbol{g}\,)$, where $\underline{X}(t)$ is the vector of all the phase variables, and $\boldsymbol{g}$ is the vector of all the parameters. Important parameters in the vector $\boldsymbol{g}$ are the operating parameters such as inlet subcooling controlled via carry-under and bleed temperature, system pressure; geometric parameters such as core height, riser height; and modeling parameters such as number of nodes, order of the assumed spatial profiles, etc.

The set of equations thus obtained is coded in the MATLAB environment. This allows an efficient capability to analyze the model. Specifically, the model developed has being used to perform the following:

1. Steady-state (fixed point) calculations [by setting $\underline{F}(\,\tilde{\underline{X}}\,;\boldsymbol{g}\,)=0$, where tilde denotes a steady-state value]. This requires the solution of a set of nonlinear algebraic (transcendental) equations.

2. Frequency domain (linear) calculations using classical stability analysis. This requires the evaluation of the eigenvalues of the Jacobian matrix, $\partial\underline{F}$. This step is also carried out using MATLAB.

This MATLAB environment hence provides an efficient approach to perform several steps in the comprehensive analysis of the flashing related instabilities, which would otherwise require a separate user developed code for each step. Preliminary simulations using the model show that it can capture the location of flashing in the experiments conducted on the Dodewaard reactor very well.

The set of reduced equations for modal neutronics for the in-phase and out-of-phase oscillations have already been developed. The coupling between neutronics and thermal hydraulics will be carried out during the second stage of the project.

As part of the international collaboration of this project, experiments are being conducted at CIRCUS facility of the *Kramers Laboratorium voor Fysische Technologie* at the *Delft University of Technology* (DUT) in the Netherlands (at no cost to DOE). Experiments are being performed covering a wide range of heat flux, flow rates and subcooling. Comparison of the experimental data with the prediction of the model will

be carried out during the second and third phases of the project.

Along with the proposed collaboration with Delft University of The Netherlands in the area of experimental work on flashing related instabilities at the facilities in Delft, collaboration has also been developed with Professor Dieter Hennig of PSI (Switzerland). A student of Professor Hennig (a Ph.D. candidate at PSI) is currently visiting UIUC and carrying out research on extending the model for two-phase nuclear coupled density wave oscillations to allow drift flux model to simulate two-phase flow and using the lambda-mode for neutronics analysis (as opposed to omega mode used earlier by Karve). While at UIUC he will also carry out stability and bifurcation analyses of the extended BWR model.

Tasks completed and results obtained thus far were presented at the ANS Annual Meeting in Milwaukee, WI, in June 2001.